

Assurance of COTS Boards for Space Flight - Part I

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Abstract

Space Flight hardware and software designers are increasingly turning to Commercial-Off-the-Shelf (COTS) products in hopes of meeting the demands imposed on them by projects with short development cycle times. The Technology Validation Assurance (TVA) team at NASA GSFC has embarked on applying a method for inserting COTS hardware into the Spartan 251 spacecraft. This method includes Procurement, Characterization, Ruggedization/Remediation and Verification Testing process steps which are intended to increase the user's confidence in the hardware's ability to function in the intended application for the required duration. As this method is refined with use, it has the potential for becoming a benchmark for industry-wide use of COTS in high reliability systems.

Introduction and Background

The Spartan 251 is a vehicle which provides experiment platforms for instruments with relatively short (days to weeks) mission lifetimes. The Spartan project is expected to provide experiment platforms which have a fast development cycle time (less than 3 years) and a low cost. To meet this challenge the project looked to COTS computer systems primarily as a solution to the schedule challenge.

Schedule improvements were hoped to be realized because so many of the development activities would not be needed: circuit design, breadboarding, troubleshooting, parts procurement and board assembly. The software required was standard. It would also require development activities and specialized skills to operate it.

COTS have as many definitions as there are people to define it. The COTS being implemented by Spartan 251 are fabricated boards. Some of the boards being used are custom designed and fabricated by an outside vendor and they were not considered COTS during this assessment. The entire system is called the central processing unit electronics (CUE box), and provides command and data handling for the spacecraft.

The lead CUE box designer identified a CompactPCI bus based system because it provided several system and software advantages. Two arrangements were considered (Figure 1 and 2) based on the use of 6U (6.3" x 9.18") or 3U (3.94" x 6.30") sized boards.

There were no boards identified at the time, with prior flight history so a variety of products were purchased. Based on how they performed individually, together and after environmental testing, the suite of boards would be selected. Table 1. lists all of the COTS boards that were purchased.

COTS Assurance Background and Approach

NASA and the aerospace industry have learned a lot about failure modes in electronic parts and boards that result from the stresses of use in flight environments. Military, NASA and Industry specifications and standards exist which try to prevent products with flaws, which cannot independently survive high and low temperature extremes, thermal cycling, shock and vibration, vacuum and other environmental conditions, from being applied in flight hardware. Testing of high reliability parts exercises them using maximum electrical ratings. Qualification testing is done by sampling a production process and is considered applicable to subsequent lots from that process for some length of time (one or two years). The goal is to increase system reliability by reducing the number and/or size of failure causing flaws and to characterize the quality of parts produced by a given set of processes.

The same philosophy can be applied to evaluating the reliability of COTS boards however since COTS products are not produced with reliability as a priority, the methods are not the same. The processes producing the hardware are not known to be controlled or are changed frequently over time (one or two years), without notice to the users. It must be assumed that COTS boards will never be able to withstand flight environments "independently". They are designed and built to operate in on the ground and are often augmented with heat dissipating mechanisms such as fans and heat sinks to enable them to survive in a 25°C environment. Once the fan is removed, it is likely that the

Figure 1. CUE Configuration A, 6U Boards

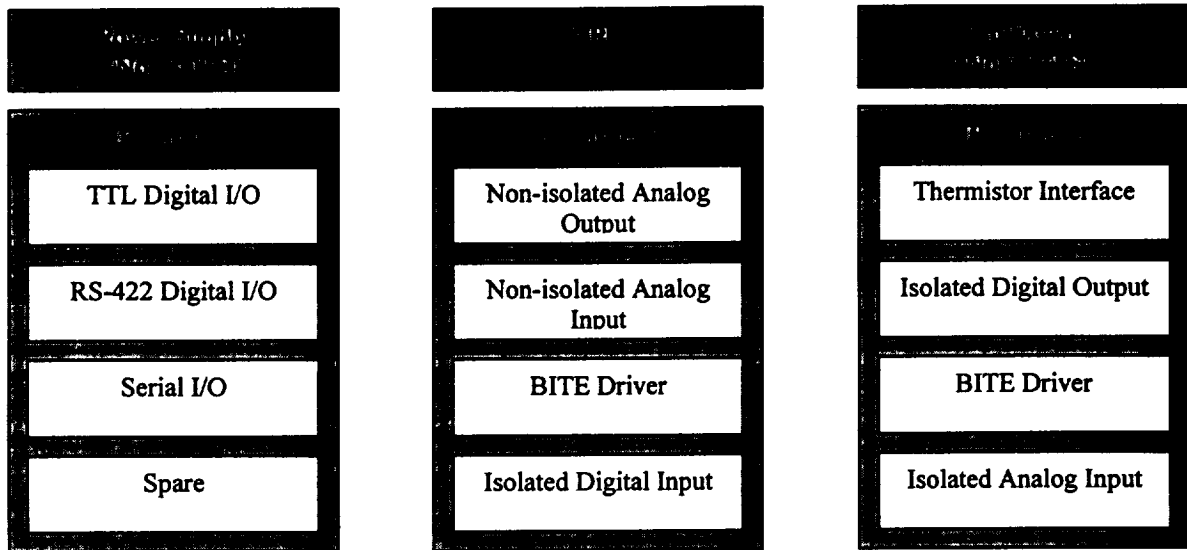
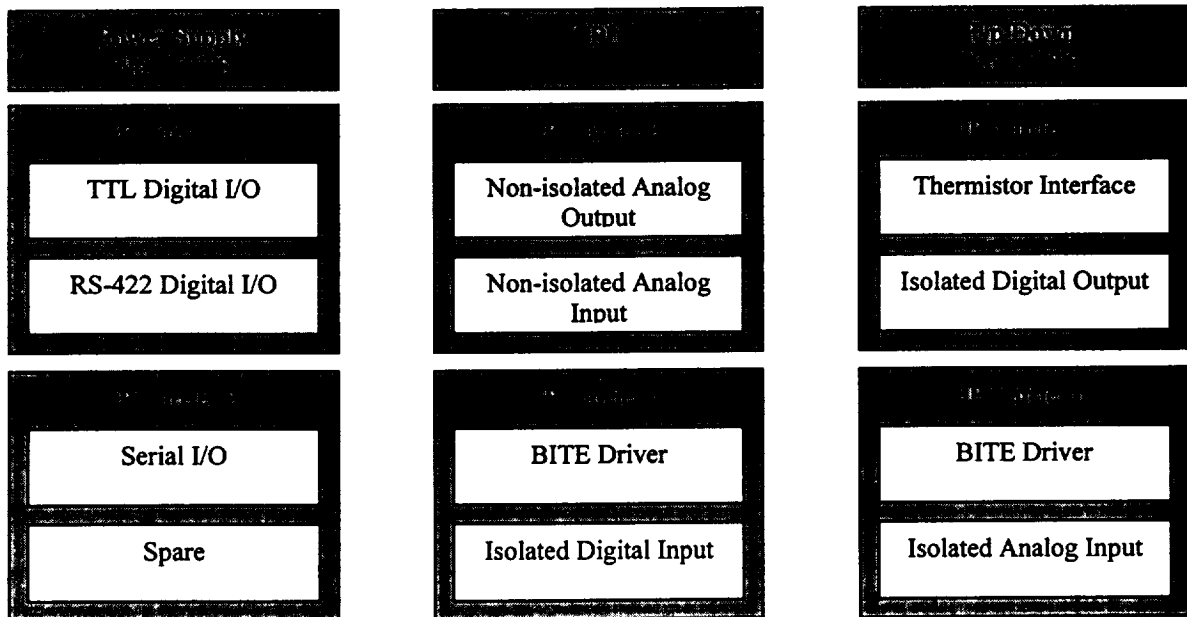


Figure 2. CUE Configuration B, 3U Boards



temperature rating given by the manufacturer will be exceeded, from component self heating. Certainly the individual parts cannot be tested to their electrical limits because they are in a circuit configuration which physically precludes this. While we test high reliability parts using known maximum electrical, thermal and mechanical conditions, we must test COTS boards in a wide variety of operational modes to expose them to

the variety of electrical stresses that they may see in application. Given that the thermal environment will have to be controlled, whether through the use of fans, heat pipes or other methods, and that deriving a test plan that addresses all possible software driven operational modes is non-trivial, the assurance engineer will realize that each COTS board in a given application should be considered unique.

Table 1. COTS Boards Purchased

Board Type	Part Number	Manufacturer	Function
6U Processors	CR6400053NBC	OR Industrial Computers	Compac PCI Pentium Board
6U Processors	CTM6	OR Industrial Computers	I/O Transition Module
6U Processors	ZT5510C4R3P3S1M3	Ziatech	CPCI Processor Board
3U Processors	CPCI-3603 (103095)	Force	POWERCORE/CPCI Processor board
3U Processors	CPCI-3740 (104912)	Force	POWERCORE/CPCI Processor board (233MHz)
Memory	104949	Force	POWERCORE/CPCI memory board
IP Carriers	CPCI-200-FP	SBS Greenspring	6U IP Carrier Board
IP Carriers	CPCI-IPC	Alphi Technology	3U IP Carrier board
IP Carriers	CPCI-SIP	Alphi Technology	3U IP Carrier board
Analog Input	IP-320	Acromag	Analog Input
Analog Output	IP-220-16	Alphi Technology	16 channel Analog Output
Digital I/O	IP-UNIDIG-E-48	SBS Greenspring	DIGITAL I/O
Digital I/O	IP-UNIDIG-HV-8I16O	SBS Greenspring	DIGITAL I/O
Digital I/O	IP-UNIDIG-D	SBS Greenspring	DIGITAL I/O
Digital I/O	IP-OPTO DRIVER	SBS Greenspring	DIGITAL I/O Optical Driver
Digital I/O	IP-445	Acromag	32 Channel, bus isolated Digital Output
Digital I/O	IP-440-1	Acromag	32 Channel, bus isolated Digital I/O +/- 4 to +/- 18 Vdc
Serial I/O	SCC-04B	Alphi Actis Technolg.	Quad RS422 serial interface
Serial I/O	IP-Serial	SBS Greenspring	Serial I/O
Serial I/O	MP-Serial	SBS Greenspring	Synch/Asynch Data Com
Thermistor IF	IP-Thermistor	SBS Greenspring	Thermistor card

Since we cannot control the quality of COTS products we need to understand their limitations and control how they are applied. Sealed enclosures can provide protection from vacuum effects and may provide a structure in which mechanisms such as fans or fluid pumps can be used for thermal management. Mechanical damping should be considered at the board and box level to reduce vibration and shock effects. Shielding can be used to limit the total deposited charge from ionizing radiation. The goal is to limit the environment's contribution to flaw growth which can result in board or part failure.

The operational modes in which the system is used, are as important a consideration as is the physical environment. The operating system and the commands used will drive the electronics in ways which may be stressful to the electronics when used in specific combinations, repetitively and over time. Consideration must be given to the intended use of the hardware and how

particularly stressful operations can be minimized or avoided.

At the beginning of the Spartan 251 COTS insertion project a four step process was proposed to gather information about the capability of the boards intended for use to survive the intended environment and how ruggedization or failure mitigation approaches could be validated. This flow is shown in Figure 3. Lessons were and are being learned along the way that have expanded the original definitions assigned to each step. The elaboration described here is intended to describe details about the first two process steps and some of the lessons learned during their implementation. It is hoped that lessons learned while implementing the last two, Ruggedization/Remediation and Validation, will be similarly documented and fed back to improve the process.

Though the flow chart shows a series relationship between Characterization and Ruggedization/Remediation we found that it was very valuable to start considering ruggedization options well ahead of time, even before the characterization data was collected. It helped to formulate questions about what the most serious concerns were and allowed time for planning. For example, we know that it was very possible that the processor would need an augmented thermal path because it was intended to be used with a fan and heat sink. This lead the mechanical team to start considering mechanical impacts that heat pipes and other thermal management augmentations would have on the closely spaced boards and on the CUE box enclosure.

Procurement

As noted above, the boards were selected by the project design engineers. The TVA team became involved prior to this selection process. We first spent time brainstorming ideas about what type of information may exist that would give us insight into the board and individual part failure rate. We are accustomed to being able to witness the production process, facilities and management of companies who make high reliability parts. Due to high reliability qualification and screening requirements, these manufacturers often keep data for multiple test lots over a long period of time (3 to 5 years) and may maintain well documented traceability between incoming materials lots and finished product lots. COTS manufacturers are not driven by their main markets to keep these kinds of records or to provide the manpower required to support a NASA vendor survey. They are cost driven and will not be able to recoup costs required to change their processes to produce higher reliability parts for flight use. We decided to ask for as much data and as little variability as possible, knowing that it would be a learning experience as we went along about how much the manufacturers actually document about their product.

It is impossible to know with sufficient certainty whether or not a COTS system will be able to withstand the rigors of space flight use before it is characterized through testing. To realize the schedule benefits which make the use of COTS

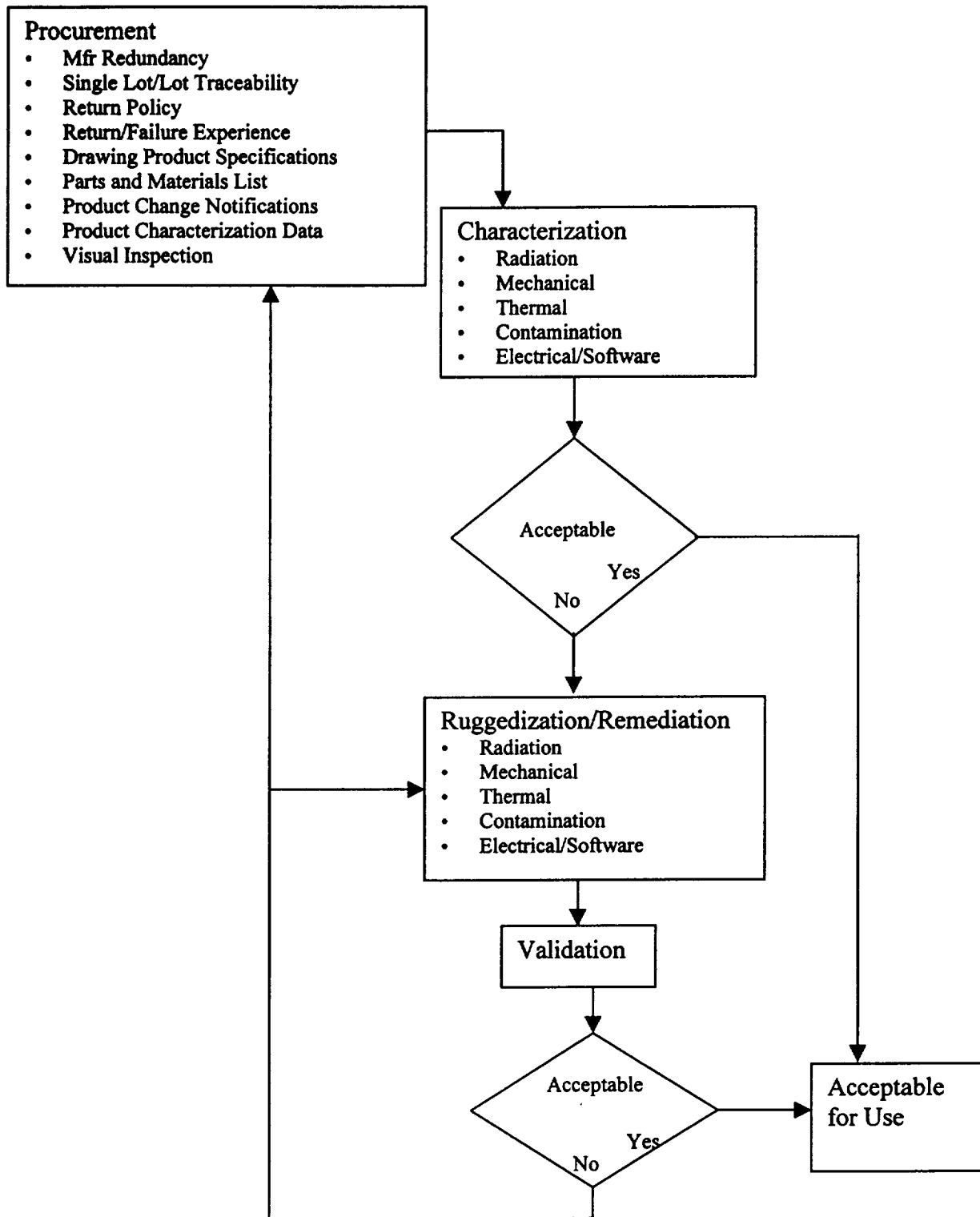
so desirable, a variety of systems or boards should be procured to increase the chances that the project will have a full compliment of boards to use when the testing is completed. This was done especially with respect to key boards such as the processor and the IP Carriers.

Single assembly lots and single lot/date codes for components used to build up the boards were requested. Single lot/date code at the part level was not available at this time however the industry is starting to respond to this need and individual vendors are specializing in "custom built", ruggedized COTS boards where lot control can be implemented. A single assembly lot was available for the boards, however the vendor(s) that were amiable to this indicated increased delivery schedule to meet this requirement as well as increased cost. Sequential serial numbers were available.

The user should be aware of the vendor return policy prior to procurement. In most cases where commercial product is used, flight, spare, and ETU samples are purchased at the same time to avoid delivery driven schedule delays. This increases cost risks. Depending on the vendor's policies, unopened, unused hardware may be returnable when characterization testing shows critical or unavoidable failure modes or other reasons for not using the product. Most of the vendors used on this project were flexible in their return policy since the boards could be resold on the commercial market if they were unopened. Some of those that offered a return policy gave only account credits which did not allow the project to recoup funds for returned items.

A thorough review of product specifications, when available, should be performed during the design cycle. Documentation beyond what is available through the marketing literature is often not available. Critical performance parameters, not defined by the manufacturer, may need to be requested. Careful consideration must be given to product obsolescence of the higher level assemblies, as well as critical component(s) (i.e. microprocessor and peripheral devices). Significant changes may be made to the product without your knowledge to keep it current with the changing platform environment.

Figure 3. COTS Insertion Process Flow



An "as built" parts and materials list should be requested from the vendor prior to procurement. The purpose of this is two-fold. First, potential contaminants can be identified such as outgassing plastics used for connector back shells, epoxies, and cleaning solvents. Second, this allows a parts list review which highlights potential reliability hazards or concerns. Parts and materials lists were requested from the vendors selected for this project, however they were not provided nor were they offered for sale. When a problem was found with a specific part during testing, the manufacturer was able to provide part specific information.

The user should request to be made aware of product changes that would affect their design. Engineering changes may or may not be adequately reflected by the documentation. It may be the case as well, that documentation such as circuit or layout drawings must be requested or purchased separately. Change notifications (controlled) were not available to the project because it was not considered a volume customer. A case of out-of-date documentation was found for two board types. One set of documentation did not match the revision letter printed on the board and the other board contained an un-insulated jumper wire that was not part of the documented configuration.

The user should obtain all characterization data available from the manufacturer. Depending on a vendor's participation in "high reliability" markets, they may or may not maintain quality or reliability data. Some manufacturers perform acceptance testing and some that ruggedize their products for harsh environments have qualification data to prove the effectiveness of their approaches. Many manufactures of COTS electronics do neither and do not have performance data available. No vendors provided existing characterization data for the boards bought for Spartan 251.

As COTS find increasing use on flight hardware, historical data will begin to accumulate. At this time this is already occurring and it is prudent to contact NASA and military organization that may have use the products you are considering, to learn about their experiences. It is important to remember though that most COTS products are not controlled for quality or designed for reliability and cannot be qualified by similarity.

Finally, the boards should be visually inspected upon receipt. One should verify that the product ordered was the one shipped and that deviations from expected configurations are noted. Look for obvious flaws such as poor soldering or stress on leads from unsupported parts. Solvent residue and corrosion should be noted. Use this opportunity to try to identify as many of the parts on the board as possible. Some will be easy to identify and may even have a lot date code identified while others will not be marked at all. Use this information to create a part map for future reference (An example is shown in Figure 4).

It is important at this stage to be sure that all storage and handling areas where these boards will be kept, must be electrostatic discharge (ESD) controlled. Packing materials must be controlled as well. It might be prudent as well at this point to set up a controlled

system for stocking the COTS hardware. If the testing goes well and some "gems" are identified, other projects will be anxious to absorb the spares.

Characterization

The boards must be characterized in order to understand the ability of the "as received" units to withstand the intended application and environment and to understand the engineering challenges associated with providing risk mitigation paths for the hardware. Characterization involves understanding their performance with respect to ionizing radiation, mechanical shock, vibration and temperature. Assessments must also be made with respect to temperature ratings of the boards, increases in ambient temperatures due to self heating, sources of contamination, concerns with respect to use in vacuum, and electrical performance such as power consumption and timing considerations.

Since COTS hardware is normally designed for terrestrial applications which maintain temperatures around $25^{\circ}\text{C} \pm 15^{\circ}\text{C}$ (although "ruggedized" boards and individual parts may have much wider temperature ratings) their ability to withstand the vacuum, thermal, mechanical and radiation environment are unknown until the board is tested. Characterization testing then must be considered to be destructive and extra boards must be

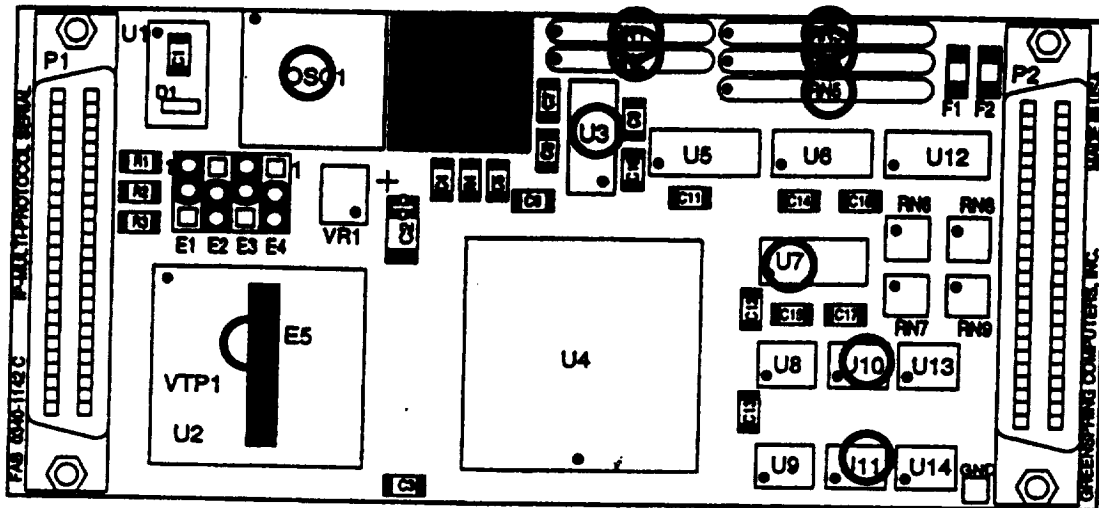


Figure 4. Part Map

procured for it. The project referred to these destruct units as Martyr boards.

Radiation Characterization

The first step is to perform a susceptibility assessment of the radiation environment. Based on the mission launch date, duration and orbit, the radiation environment can be defined. This definition should provide the severity of the proton, gamma ray and heavy ion environment that will allow proper determination of the fluence to use during Single Event Effect (SEE) testing. SEE testing will show if charged particle impacts will cause the electronics to temporarily (upset) or permanently fail (latchup, lockup, etc.). The environment definition should also describe the total accumulated (electron) dose expected so that the board's ability to withstand deposited charge can be evaluated and/or shielding can be designed. Total Ionizing Dose is not an issue for short duration missions in low earth orbits. The radiation assessment done for the Spartan 251 mission showed that the primary radiation environment risk was due to protons.

Following environment definition, application and mission-specific radiation test procedures must be prepared. The test procedure must be based on the conditions of the application and should simulate in-flight usage of the COTS hardware. COTS hardware cannot be "qualified" as a technology like electronic parts are. They must be validated on a lot-by-lot basis so testing

must represent the application that the parts will be used in, to the greatest extent possible.

The proton testing consists of high fluence and low fluence testing. High fluence proton testing provides data on component susceptibility, rate prediction data and total accumulated dose. High fluence testing is destructive. For the Spartan project, 63 MeV incident protons were used with a fluence of $3.8E10$ protons/cm². Low fluence testing is performed on the flight units and is not destructive, however the board is considered to have accumulated total dose. Low fluence testing provides data which gives a reasonable confidence that the flight boards have a radiation susceptibility that is similar to that shown during the high fluence testing.

Mechanical Characterization

Mechanical characterization of the Spartan CUE Box and its COTS electronics boards was done using both structural analysis and mechanical vibration testing. Resonance frequencies of vibration, random vibration, steady state and transient loading and thermal loading (simulating Space Shuttle launch and landing conditions) are applied in the testing of these items. Excessive deformation, excessive mechanical cycling of the boards and failure of the solder joints are the critical reliability concerns. This is especially the case for the Spartan 251 project because most of the components on the COTS boards are surface mounted. The boards need to survive one shuttle flight.

Qualification and acceptance vibration levels were defined for the CUE Box. The qualification level is used on the Martyr boards and the acceptance level is used on the flight boards. The boards will be held in the CUE box along their side edges, along the bottom edges and at the top two corners of each board. Wedge-lock type card retainers normally used in space flight boxes cannot be used because only 0.10 inches of edge space are available for securing the boards in the box. A less robust, commercially available, edge restrainer was baselined for use.

The PC boards should have resonance frequencies of vibration that are sufficiently different than those of the CUE box in which they are secured so that the resonance frequencies of the boards and box do not couple. If they do couple, excessive mechanical excitation could occur and cause board failure. Structural Finite Element Models (FEMs) of the boards are developed and used in all of the structural analyses involving the boards and the CUE box. Modal testing of each COTS board, using free-free edge conditions is used to provide data that can be used to adjust the FEMs so that they accurately represent the board under test.

Three-axis random vibration testing is used to characterize the integrity of each COTS board and each module attached to the Carrier boards. These tests are performed in a test fixture designed to secure the boards using the same hardware and configuration that will be used in the CUE Box application. Board preparation steps include: staking the components, soldering in socketed parts, conformal coating of the entire board (except at specified masked off areas) and installation of connectors as applicable. The staking, soldering and conformal coating steps will be duplicated for the flight boards. Care must be taken when applying solder, coating and staking materials so that the temperature ratings of the components are not exceeded.

A full board electrical functional test should be performed during and after each axis of testing. Careful visual inspections must be made to validate that solder joints are not damaged. Photographs should be taken for this purpose.

Maximum displacement of the 6U IP Carrier boards was a concern. On the 8-slot backplane chosen for the CUE box, two IP Carrier boards will be in adjacent slots with only 0.1 inches

clearance between them. A random vibration analysis was planned for the 6U IP Carrier using the FEM, which includes edge constraints that estimate the fixity that the actual board will have in the CUE box. This analysis should provide a good idea of where to expect the maximum displacement of the board under random vibration loading.

A random vibration test can then be performed on the 6U IP Carrier with an accelerometer attached to the location that the FEM analysis predicts maximum displacement will occur. The displacement data will be used for the following two purposes: to verify whether or not the two boards will contact during vibration and to update the FEM. The edge conditions simulated in the FEM will be modified so that the FEM random analysis results match the random test results. Sine sweep test data obtained during the test is also used in the adjustment of the edge restraint simulation.

Thermal Characterization

Thermal characterization is performed to get an understanding of the thermal effects on the components and materials due to: self-heating by the electronic components and the ambient temperature, the availability of thermal paths and the lack of convective cooling in vacuum and zero G. Theoretical and empirical analysis must be done to establish the thermal conditions that will be seen by the boards in flight configuration, in vacuum. Worst case power dissipation's should be used for the analysis to simplify obtaining the power data.

Since the design margins, electrical and thermal are not known for COTS boards, it is important to measure these conditions for the boards received. Infrared Imaging can be used to measure radiated emissions from hot objects such as the parts on the board. These radiated emissions, which are visible in the infrared frequency range, can be translated to temperature provided the emissivity of the material is known. Extreme care must be taken when collecting this data to avoid stray sources of reflected emissions and to isolate the subject from cooling mechanisms (such as moving air) that will not be available in the flight application. An understanding of how the camera works and its limitations with respect to accuracy and fidelity,

Thermocouples were also put in place to track the accuracy of the temperatures calculated from the IR data. The delta between these two forms of temperature data varied between 0.35°C and 3.83°C (averages for each board). The temperatures measured were in the range of 23°C (ambient temperature) to 62.9°C. Comparisons between the temperatures measured and the part ratings (at least those which could be identified) indicated that there was probably little to no thermal margin at 60°C ambient temperature (the project's maximum operating temperature requirement). The thermal margins were based on the addition of 27°C to the measurements taken at 23°C ambient. Figure 6 shows the IR imaging set-up.

Thermal modeling can be used to predict or reveal thermal problem areas in vacuum (or in a sealed enclosure) that could not be measured during testing. The results of these models may be selection and design of an alternate enclosure or additional thermal management assemblies. Additional thermocouple measurements may be required after the results of the thermal modeling are obtained. The thermal data indicated a need for additional thermal management at the board and/or part level. The thermocouple and IR data was provided to the thermal engineering group to both validate their models of the thermal system and to help them begin to design ruggedization hardware.

Contamination

Since COTS boards are generally not designed for use in applications that are extremely sensitive to contamination, the COTS hardware must be reviewed and tested for sources of contamination and moisture. The first place to collect this data is from the manufacturer where it may or may not be available. If the materials cannot be adequately documented in this way, testing is required.

First the boards should be baked out in an oven at the highest temperature allowed by the manufacturer's ratings. This should be done for as long as the schedule will allow (one to two weeks for maximum temperatures of 50°C). An instrumented outgassing test then should be run on the baked out board to verify that the contamination level is acceptable. Following bake outs, the boards should be conformally coated in accordance with NASA standard procedures. Extreme care should be taken to avoid exposing components to temperatures beyond their rating.

Summary

By using this methodology for purchasing and characterizing COTS boards, a project should be able to understand the most critical vulnerabilities of the system in the space environment and will be able to create a ruggedization and/or risk reduction plan that addresses these quantified concerns. Theoretical and empirical methods can be used to simulate environments without sacrificing hardware. Since qualification testing has limited application in the case of COTS, it is important to get data for the flight units in the configuration in which they will be used.

This work was done under contract to NASA GSFC for the NASA Advanced Interconnect Program and the Spartan 251 program. Work which was performed on the Spartan 251 COTS task which contributed significantly to this paper was done by Dr. Michele Gates, Greg Martins, Dr. Henning Leidecker, Don Deibler and Beverly Settles. Their contributions are appreciated.